PERFORMANCE ANALYSIS OF IMPROVED DC-DC CONVERTER TOPOLOGIES FOR SOLAR PHOTO VOLTAIC ENERGY HARVESTING SYSTEMS

A SYNOPSIS

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S. KALIMUTHU KUMAR

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(DEEMED TO BE UNIVERSITY)

ANAND NAGAR, KRISHNANKOIL – 626 126

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1. INTRODUCTION

The Wind energy and the Solar Photo Voltaic (SPV) energy are the dominant and the abundantly available renewable energy sources. Enormous developments and deployment of renewable energy sources have happened in various countries in the past few decades [1]. The international scientific and engineering communities pursue constantly in the design and development of economic renewable energy harvesting systems particularly for the solar and the wind energy.

On account of the Wind Energy Conversion Systems (WECS) and the Solar Photo Voltaic Energy Conversion Systems (SPVECS), the SPVECS has more advantages than the WECS. The initial cost and the floor area occupied per unit power generated are high in the case of SPV systems. However, the availability of the solar irradiance throughout the year, at least in tropical countries, the noise free operation, minimal requirement of maintenance, ripple free DC voltage output, environmentally friendly while in usage are the advantages of the SPVECS systems.

These advantages lead to more and more acceptance in the industry and the pursuit for building more efficient power conversion systems based on the SPV source have encouraged continuous research and development of the systems built using the SPV source .

The primary output of the SPV systems is DC. The SPV panels are generally available in the voltage range of 15 V to 22 V with a nominal output current typically 7.5 A to 10 A making the power capacity of the panel in the range of 125 W to 220 W. Many numbers of SPV panels may be cascaded in series or parallel and SPV farms with higher voltage and power ratings can be built [2] .

An SPV source may either be used for standalone DC loads or standalone AC loads and it may be grid integrated using inverter and appropriate harmonic filters . For the purpose of powering up DC standalone loads which require higher or lower voltage level than the primary source available from the SPV farm, a power electronic converter is added in the system to step down or step up the voltage of the incoming source as per the requirement of the load. If the stand-alone load requires an AC voltage that is of higher voltage level than what is available from the source then either a boost converter followed by an inverter is used or an inverter followed by a step-up transformer is used.

The incoming low voltage DC may be first stepped up as high voltage DC and then inverted. The other option is to invert the low voltage DC and then step up the AC. The first case requires a chain of power electronic converters only. The second option needs a step-up transformer which occupies more space, noisy, requiring more maintenance and supervision and also costlier.

The 'all semiconductor' power processing schemes are preferable because of their reduced prices, reduced space and weight and so on. Thus the more preferred model of converting power from the SPV source to the stand-alone AC load is to use a step-up DC-to-DC converter and then use a solid-state inverter and a passive filter [3].

In this research some of the novel schemes of power conversion systems as applicable to SPV sources for catering to the needs of standalone DC loads, electrical vehicles as well as grid integration are discussed at length. Some novel power conversion schemes as applicable to SPV harvesting system, along with their merits are presented.

2. LITERATURE REVIEW

The findings and assessments of certain latest and exceptional investigations are proffered here and various directions of research have been followed, the SPV Application wise, Variants of DC-to-DC converter, MPPT ,Partial Resonant DC-to-DC converter and Control Schemes for converter handing renewable energy sources are some of the important research areas wherein large volumes of scientific articles have been published.

Solar PV sources may be used for standalone applications as well as for integration into the grid. There is proliferation of articles on both standalone applications and different schemes of grid integration. Some of the relevant articles are considered herein.

The authors of the article Chatterjee and Mohanty have demonstrated a grid integration scheme using a single-phase inverter is used to interface photovoltaic plant with distribution system [1]. The authors in the research article J. Kivimäki et.al, have introduced a method to estimate transient behavior of input-voltage-feedback-controlled MPPT converters for two typical design cases [2]. The authors, X. Wu et. al, in their certain research article have summarized the requirrements of the DC-DC

converter for fuel cell vehicles powertrains according to the characteristics of the powertrain and output characteritics of Fuel cell, which mainly include high voltage gain,low input current ripple ,and wide input voltage range [3]. A grid-interfaced solar-PV fed BLDC motor drive- based water-pumping system has been discussed in Antonello et al. , enabling a customer to function the water-pump at its total capacity for 24 hours regardless of climate variations. The full utilization of a solar-PV feed water pump is made possible to attain more reliable operation through a single-phase grid when solar-PV is not available. The solar energy feeds to a single-phase utility grid when the water pump is not operated [4].

The sub synchronous resonance is a phenomenon associated with the steam powered synchronous generators connected to the grid through series compensated transmission line. The authors in a research article Varma and Salehi have developed a large scale DSTATCOM that is useful for alleviating the sub synchronous oscillations. The series resistance included in the model of a solar PV panel accounts for a number of factors including the ohmic contacts of the end terminals to the silicon wafer. This series resistance plays an important role in the characteristics of the solar PV panel [5]. The authors in a research article R.Singh et al. have done an elaborate literature survey of many articles which deal with the estimation of the series resistance of the solar PV panel [6].

Integration of the renewable energy sources and particularly the solar PV sources to the national grid is an important exercise and it involves satisfying certain fundamental requirements. The authors in the research article Mishra and Karthikeyan have developed the DSTATCOM for the compensation of reactive power, nonlinear source current and the issues related to unbalanced load currents [7]. A novel control strategy for the management of the DSTATCOM has been proposed and validated by the authors in the research article Kumar et al. [8]. Another novel control algorithm for the DSTATCOM has been proposed and validated for the management of the DSTATCOM by the authors in Duarte et al. [9].

A review article covering various aspects of the DSTATCOM by different researchers have been presented by the authors in B.Singh et al. [10]. The review article compares the different DSTATCOM topologies, their design details, important results

and a comparison of the performance of different topologies, possibilities of future developments of each of them and potential applications.

A detailed survey of the available literature dealing with power electronic converters have been carried out by the authors in the research article Mumtaz et al. [11]. The authors have classified non-isolated DC-to-DC converter based on the performance parameters that are analysed using MATLAB Simulink. Control techniques that Include PID, SMC, Model Predictive Controller, State Space Modelling, and Fuzzy Logic Controller are also discussed considering the parameters settling issue, response time and complexity while integrating with non-isolated DC-to-DC converter in power systems.

In this article Sutikno et al., the performance of 7 DC-to-DC converter topologies has been studied. The main challenges of these topologies for low-power SPV applications are discussed [12]. The selected converters have voltage gain of greater than 15 times. A DC-to-DC converter topology with a high voltage gain has been presented by the authors in the research article Gnanavadivel et al. [13]. While offering a high voltage gain the topology keeps within limits the voltage stress on the semiconductors.

Further, a switched inductor DC-to-DC boost converter has been proposed and validated by Vaidya [14]. This work is specifically meant for developing drives for the DC machines which do not use renewable energy sources. Multilevel boost converters are used for high voltage gain with reduced voltage stress on the power semiconductors, by the authors in the work Premkumar et al. [15]. The authors have demonstrated a number of possibilities of parallel operation offering bi directional power transaction as well. A novel full bridge type of DC-to-DC converter topology has been proposed and validated by the authors in the research article by Plesko et al. [16]. The authors have been keen in reducing the cost, the size and the weight of the proposed converter system so that in a moving vehicle these aspects do not hinder the overall performance.

An isolated DC-to-DC converter with an Z source on the front end has been proposed and validated by Chub et al. [17]. The proposed scheme uses a single power electronic switch. The isolation between the source and load sides have been created by the usage of an isolation transformer that acts as a voltage boost mechanism as well.

The authors of the research article Mageshwari et al. have presented a novel Buck-Boost Converter for Residential PV Application [18].

Partial Resonant Inverters (PRI) are used in DC-to-DC converters which use a high frequency AC link. The PRI based DC-to-DC converters have the advantages are higher power conversion efficiency, it does not require an AC link transformer hence small in size, mass and cost, Provides an isolation between the source and the load side even in the absence of a transformer and high voltage gain. Because of these advantages many researchers have adopted the PRI for diversified applications. Some of the key applications are outlines here.

In a research article by the authors in Mozaffari and Amirabadi the authors have presented the detailed design and development of a PRI based power converter. The PRI can be used for interfacing solar PV sources or any other renewable energy source in the form of DC [19]. A combined series and parallel resonant circuit proposed and validated by the authors in Tandon et al. [20]. In this work the partial resonance pulse was created by the series LC circuit and this helped to achieve zero current switching in the push pull, current fed and converter arrangement. A series resonant circuit with a coupled inductor boost topology has been proposed and validated by the authors in the research article Park [21]. The system gives the advantages of a high voltage gain while also guarantees isolation between the source and the load ports. Two different topologies for AC link DC-to-DC converters have been proposed and validated by the authors in Keyhani and Toliyat [22]. One of the two variants demonstrates a non-isolated AC link converter with an inductor and a capacitor in parallel.

Control systems play an important role in managing power electronic converters handling renewable energy. The role of control systems is wide and vital and typically some of the responsibilities of the control systems are the regulation of terminal voltage of sources, regulation of the speed of motors driven by power electronic converters, MPPT while harvesting renewable energy. A highly advanced control scheme that incorporates a fuzzy logic scheme, a PID part and a SMC all put together has been proposed and validated by the authors in the research article Van [23]. The authors of the research article Gheisarnejad and Khooban have presented a novel non integer PID

controller that uses the deep deterministic policy gradient algorithm suggested for the management of the tracking task of a robot [24].

A novel, super twisting, nonlinear fractional order PID assisted SMC has been proposed and validated for the speed regulation application of a PMSM in a research article by Gao et al. [25]. The permanent magnet synchronous linear motor while powered from the AC source draws nonlinear currents rich in harmonics. The authors in the research article Pan et al. [26] have developed a resonant two degree of freedom PID controller so as to mitigate the harmonics and also to achieve the primary control objective. In a specific application of the PID controller in the area of magnetic levitation the authors of the research article Chen et al. have demonstrated the extreme seeking principle of tuning the PID controller [27].

It has been observed from the available literature that the research activities related to the solar photo voltaic sources have spread in many directions and more importantly the research activities are busy in the development of novel topologies which focus on reduced component count, size mass and cost.

Power conversion efficiency has been the focus of some authors, who have developed many power conversion efficiency modulation and control schemes. The zero voltage switching and the zero current switching have been considered the two important strategies for reducing the switching power losses. The use of the Series Compensated Buck Boost Converter (SCBBC), the Partial Resonant Inverter (PRI) and the augmentation of the solar PV source into the grid using these power electronic converters on the DC side of a DSTATACOM are not much explored. This research concentrates on these three areas of developing power electronic conversion systems using the SCBBC applicable for solar PV energy harvesting. The research also makes a study of the PRI based AC linked DC-to-DC converter for offering a high voltage DC from a relatively low voltage source typically from a solar photo voltaic source. And finally, this research also presents the method topology for integrating the solar power harvested into the grid through the DC link of the DSTATCOM. In the DC side of the DSTATCOM where the solar PV source is to be connected a power converter chain is used that offers large voltage gain, increased power conversion efficiency and stable as well. This report presents the details of addressing the research gaps identified.

3. OBJECTIVE

The main objectives of the research are as follows:

I. To design the novel Series Compensated Buck-Boost Converter using average state space modelling for a standalone DC load.
II. To design the novel Partial Resonance Inverter-based AC linked DC-to-DC converter for a standalone DC load.
III. To design novel scheme for the grid integration of the energy harvested from an SPV using a DSTATCOM
IV. To analyse the performance of proposed converters using power conversion efficiency, switching loss thus reducing size of the system

4. RESEARCH PROBLEM

Although the research focusses on the development of novel power electronic converters suitable for harvesting the solar PV source some specific methodologies and topologies have been developed and the following is the list of contributions of this research.

In the first work, a Sliding Mode Controller (SMC) based Maximum Power Point Tracking (MPPT) of Solar Photo Voltaic (SPV) Power Harvesting System using the Series Compensated Buck-Boost Converter (SCBBC) has been presented. The SCBBC offers a voltage gain as high as the generic boost converter, for the given duty cycle, but it is a partial scale converter in which a part of the power delivered to the load passes from source through the converter and the remaining part flows directly from the source to the load, and hence the power conversion efficiency is higher. Further, unlike the other existing MPPT techniques which require the terminal voltage and the output current of the SPV source, the SMC based MPPT requires only the terminal voltage of the solar PV panel.

The second work is about developing a power conversion system for harvesting the solar PV source and charging an EV battery using a novel Partial Resonant Inverter and a doubler rectifier with SMC based MPP.

In the third work a novel scheme of grid integration of the solar PV source is demonstrated in which the DC channel uses the Partial Resonant Inverter. It has been

established that the proposed system offers higher voltage gain, power conversion efficiency and smaller size, weight and cost. The active power support is provided to the load during day and the grid side reactive burden is reduced during day and night.

5. CONTRIBUTIONS

5.1 Averaged state space modelling and the applicability of the Series Compensated Buck Boost Converter for harvesting solar photo voltaic energy

The SCBBC is a DC-to-DC converter obtained from the generic Buck-Boost converter, It offers more advantages than the conventional Buck-Boost converter. The steady-state voltage gain equation of the SCBBC is the same as that of the generic boost converter.

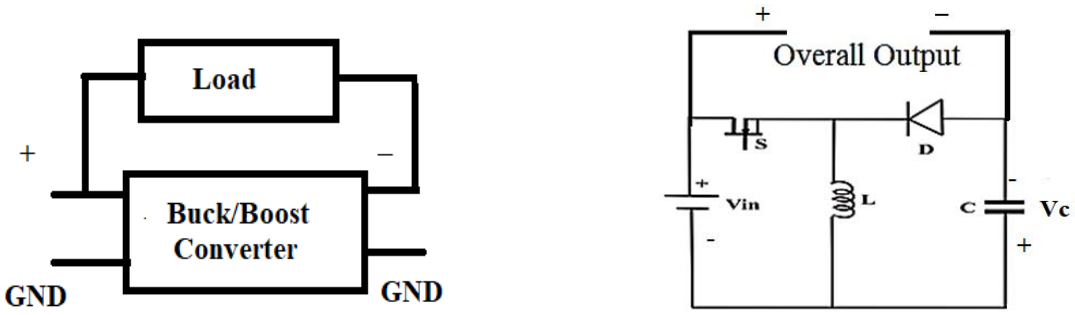

Figure 1 (a) The schematic diagram of proposed SCBBC and (b) The circuit diagram of proposed SCBBC

With the SCBBC, a part of the power to the load is supplied directly from the source, while the remaining part of the power is related to the power flow, to the load through the SCBBC topology. This two-way power flow technique improves the power conversion efficiency. Further, the size of the SCBBC can be reduced than that would be required if the generic Buck-Boost converter was used for the given power transaction. The circuit diagram and topology of SCBBC are shown in Figure 1(a) and 1(b). In the structure of the SCBBC, the positive terminal of the power supply is directly connected to the load. In contrast, the negative terminal of the load is connected to the negative terminal of the output capacitor of the converter. The block diagram of SCBBC based proposed system is shown in Figure 2.The SMC has been used for the MPPT. The steady-state voltage gain and the state-space model of the SCBBC have been derived.

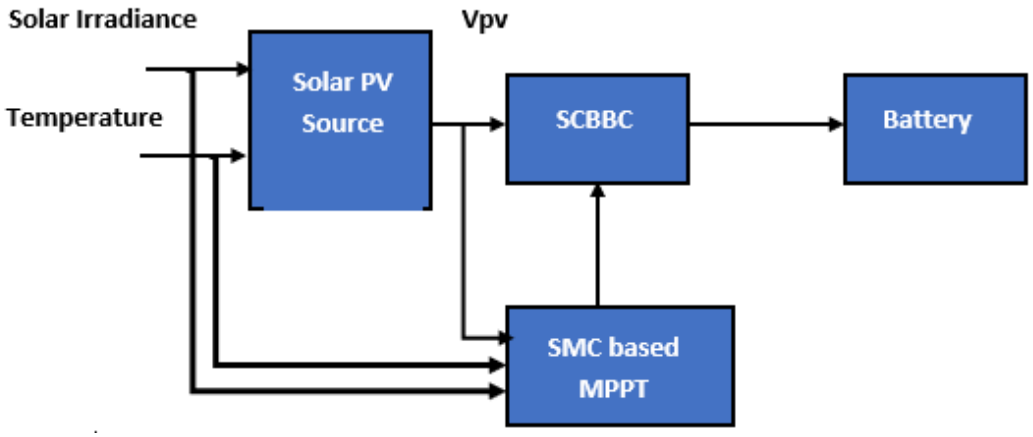

Figure 2 The block diagram of SCBBC based proposed system

The derived state-space model of the SCBBC has been simulated, and the resulting waveforms of the state variables and the output voltage have been observed the proposed topology, the SPV subsystem, and the battery are circuit modelled in the MATLAB SIMULINK platform.

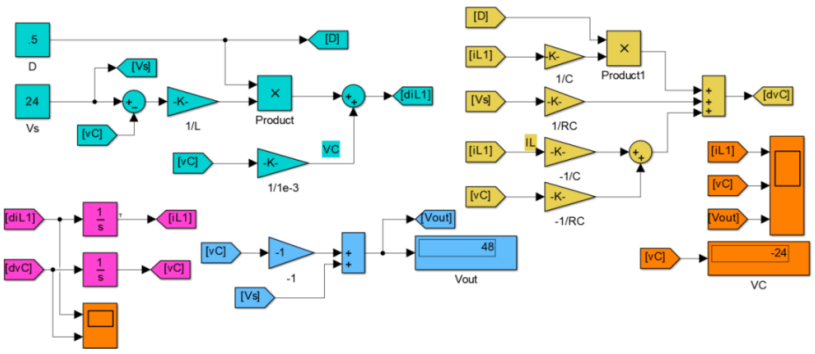

Figure 3 The State Space Averaged Model implementation in the MATLAB SIMULINK simulation environment.

The realization of the averaged state space model in the MATLAB SIMULINK environment is given in the Figure 3, wherein Vs is the source voltage or the input voltage. The final output voltage is the sum of the source voltage and the voltage across the capacitor C. The waveforms of the state variables and the output as obtained from the state-space models have been obtained with a source voltage of 24 V and a duty cycle of 0.5. This makes the steady-state voltage across the capacitor C is -24V, and the total voltage developed for the load is the sum of the source and the capacitor voltage the voltage across the load then becomes 48 V. For an input of 24 V, and for a duty cycle of 0.5, the output voltage is doubled as a boost converter. The load resistance is 48 Ohms. The power delivered to the load is 48 W. A part of the total power delivered

to the load, 24 W, is directed directly to the load, and the remaining part is directed through the converter itself. Thus, the converter component has to carry only part of the transacted power. The hardware details of the proposed system is mention in Table 1 and power through the Subsystems of SPV to SCBBC and SCBBC to Battery power conversion in an experimental prototype is mentioned in Table 2.

Table 1 Specification of the experimental prototype

Components	**Rating**
Inductor	1 mH
Capacitor	4400 µF , 63 V
Power Electronic Switch S1	IRF 540 MOSFET
Power Electronic Switch S2	2 X 6A Diodes in parallel
Battery	12 V 35 Ah two numbers in series

Figure 4 The Solar PV panel

Figure 5 The power electronic converter with the batteries.

Table 2 The power balance through the Subsystems of SPV to SCBBC and SCBBC to Battery power conversion in an experimental prototype

Solar irradiance	**Subsystem**	**Output Terminal Voltage**	**Output Current**	**Power Delivered**
500 W/m^2	SPV to SCBBC	16.7 V	3.76 A	62.8 W
	SCBBC to Battery	22.2 V	2.35 A	52.17 W
950W/m^2	SPV to SCBBC	17.1 V	6.8 A	116.2 W
	SCBBC to Battery	24.7 V	4.45 A	110 W

The SPV source of experimental prototype is shown in Figure 4 and the power electronic converter with battries is shown in Figure 5. The switching pulses applied to the MOSFET these switching pulses areas are dictated by the SMC algorithm embedded in the PIC 16F877A Microcontroller. The switching pulses reach the MOSFET gate through the Opto Isolator IC MCT2E. The voltage across the battery is shown in Figure 6.

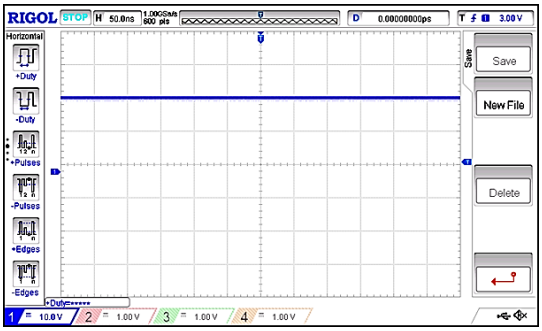

Figure. 6 The voltage across the battery

5.2 A revolutionary Partial Resonant Inverter and a doubler rectifier for harvesting solar photovoltaic sources

The harvesting of the solar PV energy for the purpose of battery charging using different power electronic converters have been demonstrated. The PRI based power conversion system is shown in Figure 7.The PRI at the front end reduces switching losses while increasing voltage gain. The doubler rectifier on the battery side further doubles the available voltage. For MPPT, the SMC has been used. The A.C. link uses a small inductor and a capacitor in parallel, reducing the size of the A.C. link compared to a large electrolytic capacitor while using a D.C. link. The conventional boost converters exhibit non linearity when operated with high voltage gain. A resonant inverter stage increases the voltage gain even with a small modulation index. This is the advantage of the proposed system.

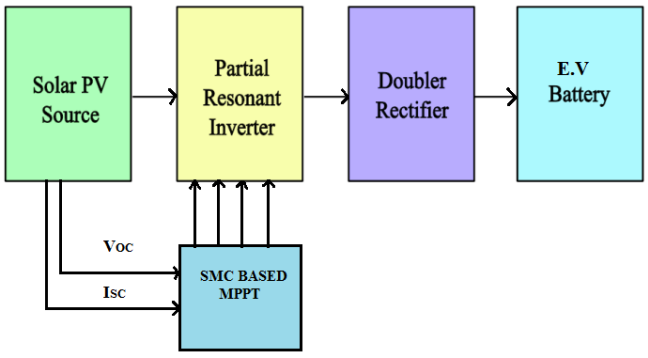

Figure 7 The block diagram of the proposed PRI based system

The resonant A.C. link on the output side of the PRI uses an L.C. parallel circuit. Depending upon the values of the LC circuit, the resonance frequency is fixed. The only controllable element in the topology is the set of power electronic switches used in the PRI and it is shown in Figure 8. The MPPT is implemented in the PRI by manipulating the power electronic switches of the PRI. The proposed system has been

circuit modelled in the MATLAB SIMULINK. Figure 9 shows the MATLAB SIMULINK implementation of a general PRI with a standard D.C. voltage source and an R load.

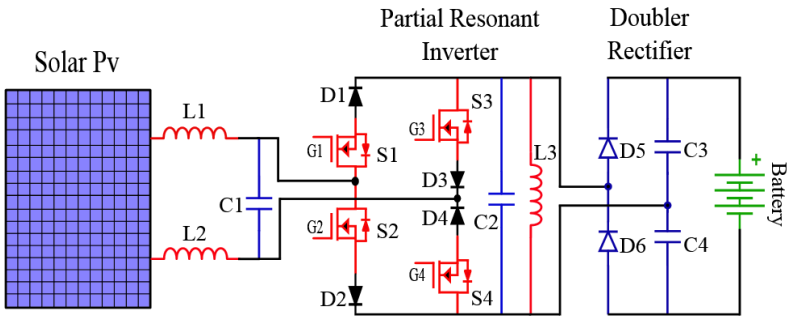

Figure 8 The circuit arrangement of the proposed system

The switching pulses are generated by a separate section using comparators that compare a triangular carrier with a reference D.C. signal. The crossarm switches 1 and 4 are switched On or Off simultaneously. Similarly, switches 3 and 2 are switched On or Off simultaneously. The set of switches 1 and 4 and switches 3 and 2 are turned On and Off contemporarily

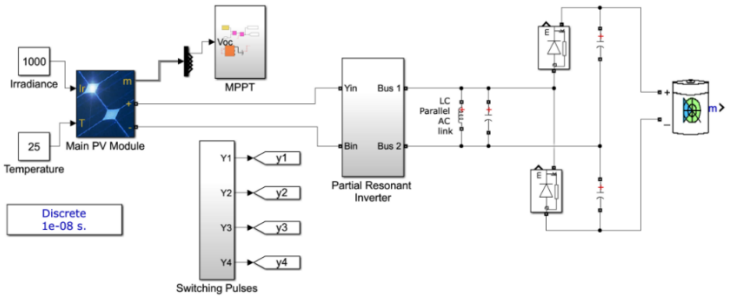

Figure 9 The overall MATLAB SIMULINK circuit modelling of the proposed scheme.

An experimental verification prototype was fabricated, and the observations confirm the efficacy of the proposed system. The PRI and the doubler rectifier were fabricated on a dedicated PCB, and the input power was drawn from a SPV source of nominal power rating of 150 W. It is shown in Figure 10. The nominal terminal voltage of the SPV module is 17 V. The maximum peak voltage across the A.C. link was observed to be 52 Volts with the 48 V terminal of the battery bank comprising of 4 X 12 V batteries. A PIC Microcontroller type 16F877A was used to hold the complete control circuit. The terminal voltage of the SPV module is logged into the

Microcontroller through the analog port A0. The switching pulses generated by the Microcontroller are routed to the MOSFETs through the optical isolator MCT2E. The waveforms were recorded from the experimental prototype, and switching pulse, battery charging current AC link voltage waveforms are presented in Figures 11-14.

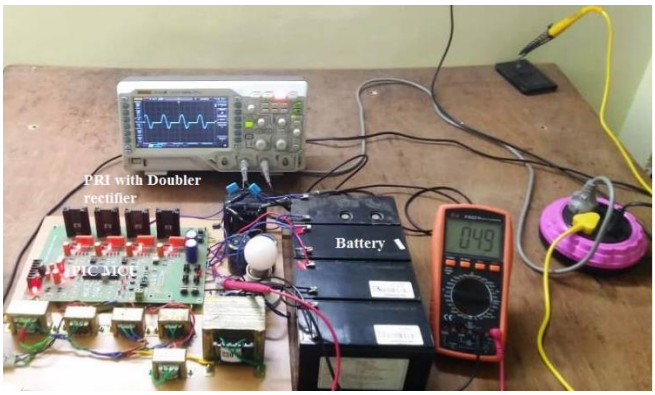

Figure 10 The experimental proto type of proposed system

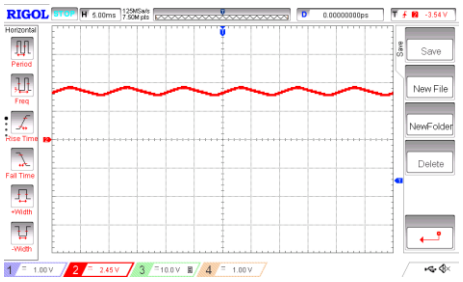

Figure 11 The Battery Charging Current

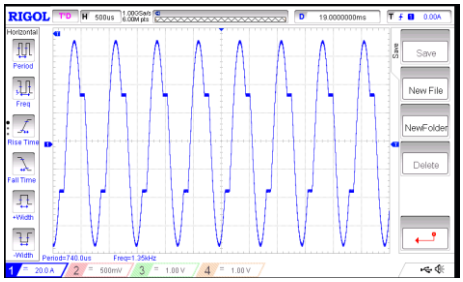

Figure 12 The A.C. link voltage with a modulation index of 0.35

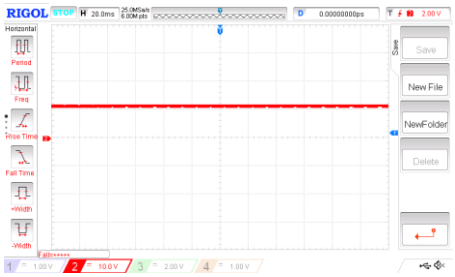

Figure 13 The input voltage

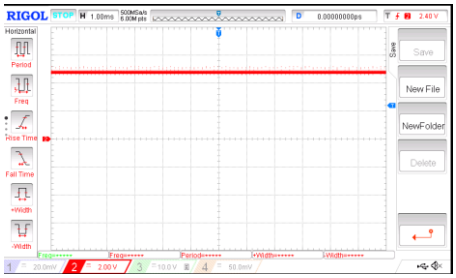

Figure 14 The terminal voltage across battery (10 : 1)

5.3 A Novel scheme for the grid integration of the energy harvested for an SPV using a DSTATCOM

The grid integration of the solar PV source involves the generation of the AC voltage in appropriate amplitude, frequency and phase so that the energy harvested from the renewable energy source is efficiently pumped into the grid. This requires

appropriate power electronic converter and control systems as well so that the grid integrating current is sinusoidal with the Total Harmonic Distortion within the allowable limits. The MATLAB model of DSTATCOM based proposed scheme is shown in Figure 15 .In the DC link the PRI and the doubler rectifier unit as shown in Figure 8 are used.

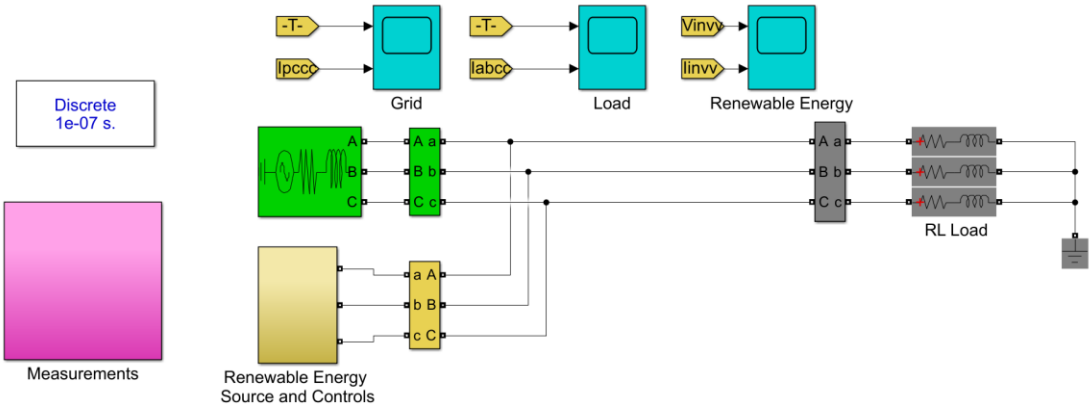

Figure 15 The MATLAB SIMULINK model of DSTATCOM

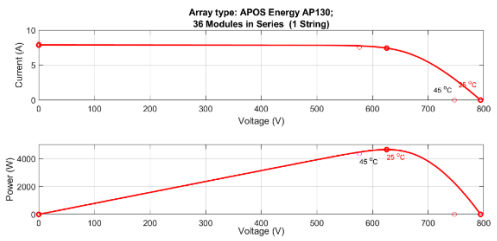

Figure 16 The Solar PV current and Voltage

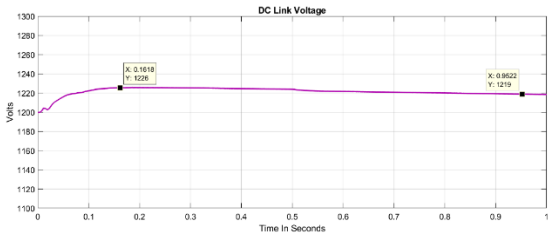

Figure 17 The DC link Voltage

The methodology of integrating the SPV source using a DSTATCOM is also presented in this work. In this work the chain of DC-to-DC converters bring the power harvested from the solar PV source to the DC link of the DSTATCOM. The chain of DC-to-DC converters uses a resonant AC link DC-to-DC converter and a doubler rectifier. The MPPT is implemented in the PRI at the front end after the SPV source. A SMC based MPPT for the SPV source is implemented in the PRI. Figure 16 and 17 shows some of the associated waveforms.

The proposed scheme makes the use of high frequency resonant AC link, that provides Zero Voltage Switching and Zero Current Switching leading to reduce

switching losses. The AC link required a small inductor and a parallel capacitor of much smaller value in the order of fraction of a Micro Farad unlike the need of a large DC link capacitor in the order of 4700 Micro Farad. The high freqeucny inductor is of a smaller size compared to a two winding transformer.

6. CONCLUSION

The SCBBC for harvesting solar photovoltaic energy has been proposed and validated . The SMC has been used for the MPPT. The steady-state voltage gain and the state-space model of the SCBBC have been derived. The derived state-space model of the SCBBC has been simulated, and the resulting waveforms of the state variables and the output voltage have been observed and presented. Another novel converter has been proposed to for high voltage and higher gain applications.

A PRI based A.C. link converter followed by a doubler rectifier is proposed for harvesting solar photovoltaic source and charging a Lithium-Ion battery. The system has been tested with simulations and experimental prototypes. It was observed that the proposed idea could harvest solar energy with the MPPT following the SMC. The PRI has proved to offer zero voltage turn On of the MOSFETs and zero current turn Off of the diodes. The system has exhibited the expected voltage achieved through the resonant A.C. link and the doubler rectifier. The Grid integrated the solar PV source using a DSTATCOM is also presented in this work. In this work the chain of DC-to-DC converters bring the power harvested from the solar PV source to the DC link of the DSTATCOM

The proposed reliable, simple, SPV power harvesting system has been designed and modelled appropriately to establish feasible objectives. The proposed scheme is evaluated through computer simulations and experiment prototypes to evaluate several performances.

7. ORGANIZATION OF THE THESIS

The organization of the proposed thesis work is clearly described as below, a general introduction to power electronic converters, derivation of voltage gain, the state space analysis, stability analysis, and the various commonly used topologies, MPPT of SPV source have been explained in Chapter 1. The details of the literature survey that has been carried out prior to the conduct of this research has been presented. Various milestone activities done in this field have been outlined under

relevant categories. A short discussion of the identified research gap is also presented in Chapter 2. Chapter 3 describes the details of a SMC based MPPT of Solar PV Power harvesting system using the SCBBC. The details of developing a system for harvesting of SPV source and charging of an EV battery using a novel PRI and a doubler rectifier with SMC based MPPT has been dicussed in Chapter 4. The details of a novel scheme for the grid integration of the energy harvested for an SPV using a DSTATCOM has been presented in Chapter 5. For increased voltage gain the proposed system uses a PRI in the DC channel between the SPV source and the DC link of the DSTATCOM. The Conclusion and the scope for future research have been provided in Chapter 6 and the References section follows

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List of Publications

1. K. Sakthivel, R. Krishnasamy, K. Balasubramanian, V. Krishnakumar, and M. Ganesan, Averaged state space modeling and the applicability of the series Compensated Buck-Boost converter for harvesting solar Photo Voltaic energy, *Sustainable Energy Technologies and Assessments*, **53** (2022) :102611.
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